Complex Dynamics of Fusion Plasmas and Nonlinear Photonics

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Motivation, Approach and Research Fields

- Physical and man-made systems are inherently characterized by dynamical complexity
- Complexity is an enabler of advanced technological applications

- Reduced models for prediction, design and control
- Qualitative overview of system dynamics for the identification of essential properties for applications
- Systematic simulations for the detailed dynamics

➢ **Fusion Plasmas**

➢ **Nonlinear Photonics**

Fusion Plasmas – EUROfusion programme

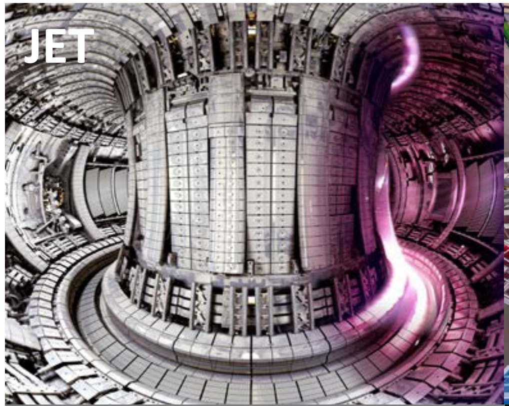
The EUROfusion programme is based on the **Roadmap to the Realisation of Fusion Energy**. The programme has two main pillars:

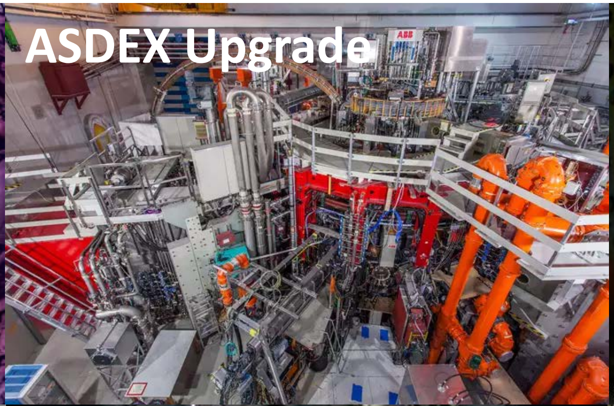
- **Preparing for ITER experiments**
- **Developing a concept for the future demonstration fusion power plant DEMO**

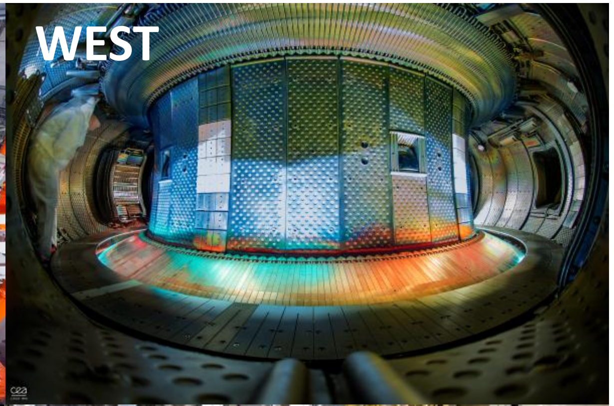
Another facet of the EUROfusion programme is to support fusion **Education and Training**.
EUROfusion is also actively involved in **Technology Transfer** activities.

EUROfusion

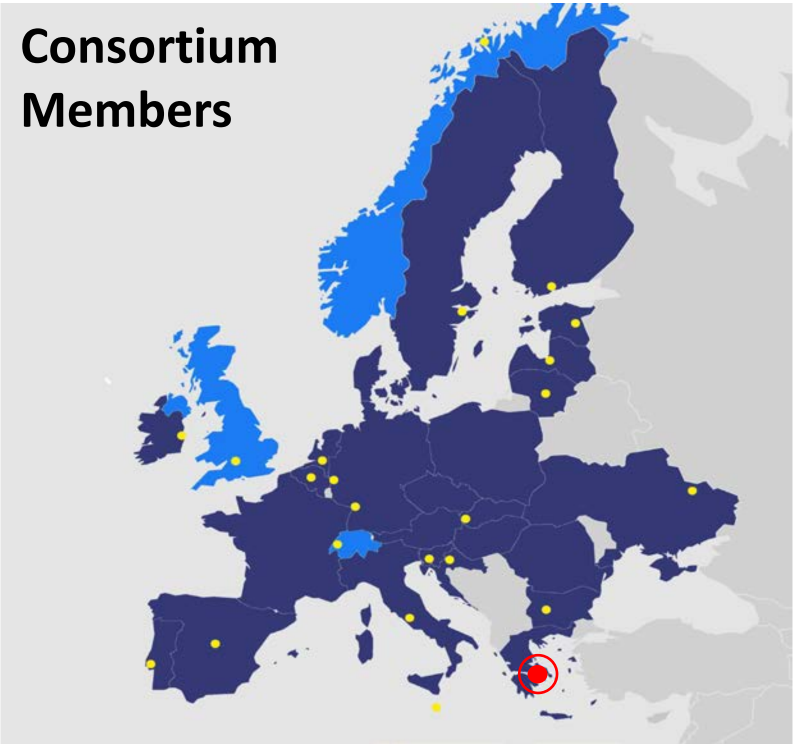
Twenty-eight members, receive **funding from Euratom** for fusion projects in accordance with their participation in the missions and experiments outlined in the **Roadmap**.







Wendelstein 7-X



Fusion Plasmas – Topics and Approach

Topics:

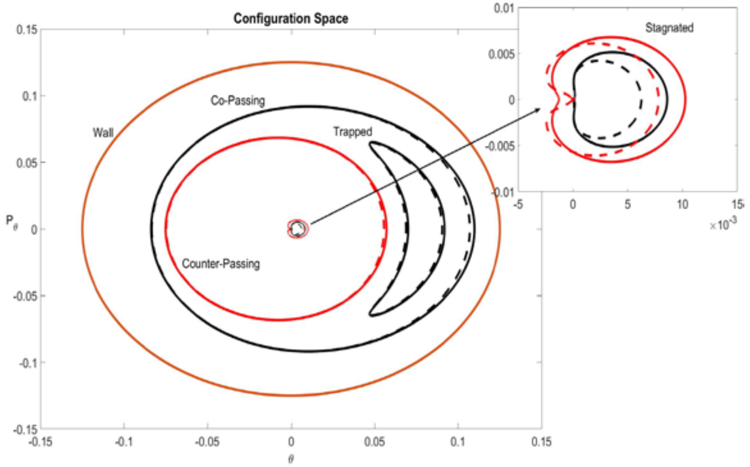
- Particle, Energy and Momentum Transport
- Fast Ion Physics
- Resonant Mode-Particle Interactions
- RF Wave-Particle Interactions
- RF-assisted Start-up

Approach:

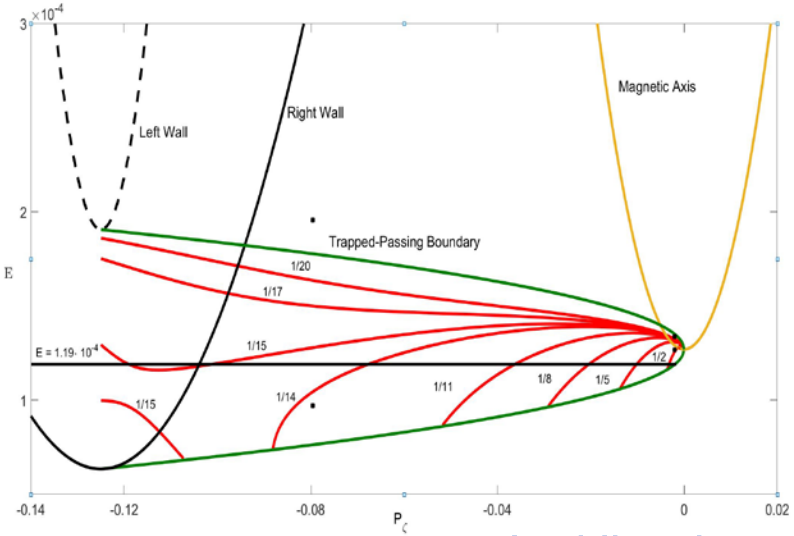
- Hamiltonian formulation of charged particle dynamics in equilibrium and non-equilibrium magnetic fields
- Action-Angle description
- Orbital Spectrum analysis
- Reduced models for transport prediction and control

Fusion Plasmas – Orbital Spectrum Analysis

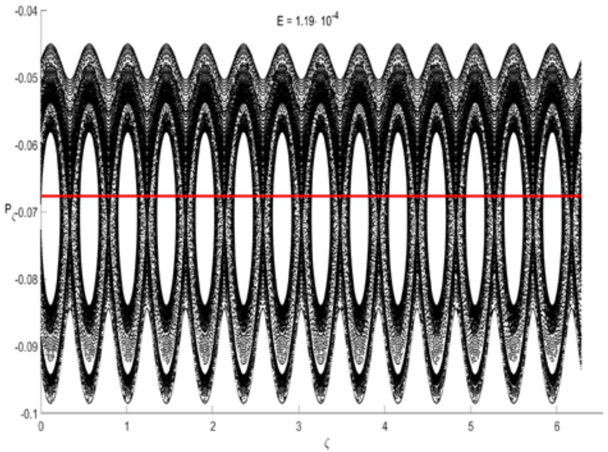
Orbital Tomography and Spectrum Analysis for Energy and Momentum Transport under Resonant Non-Axisymmetric Perturbations

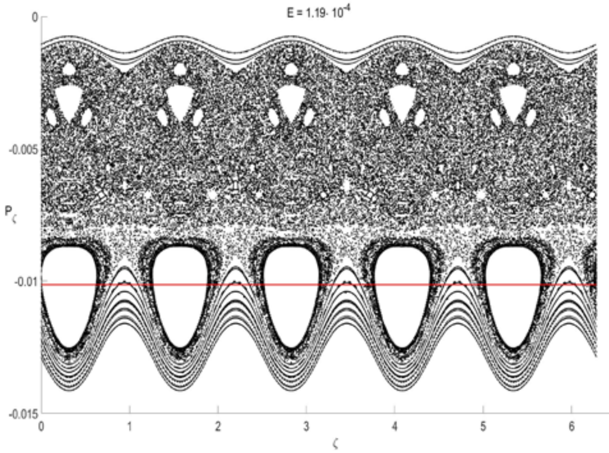


***Efficient Orbital Spectrum calculation** based on judiciously selected magnetic flux surfaces of reference. Dashed lines: approximate orbits, Solid lines: exact orbits*



***Resonance conditions** (red lines) on the **C**onstants **O**f the **M**otion (COM) orbit space (μ variable is fixed)*



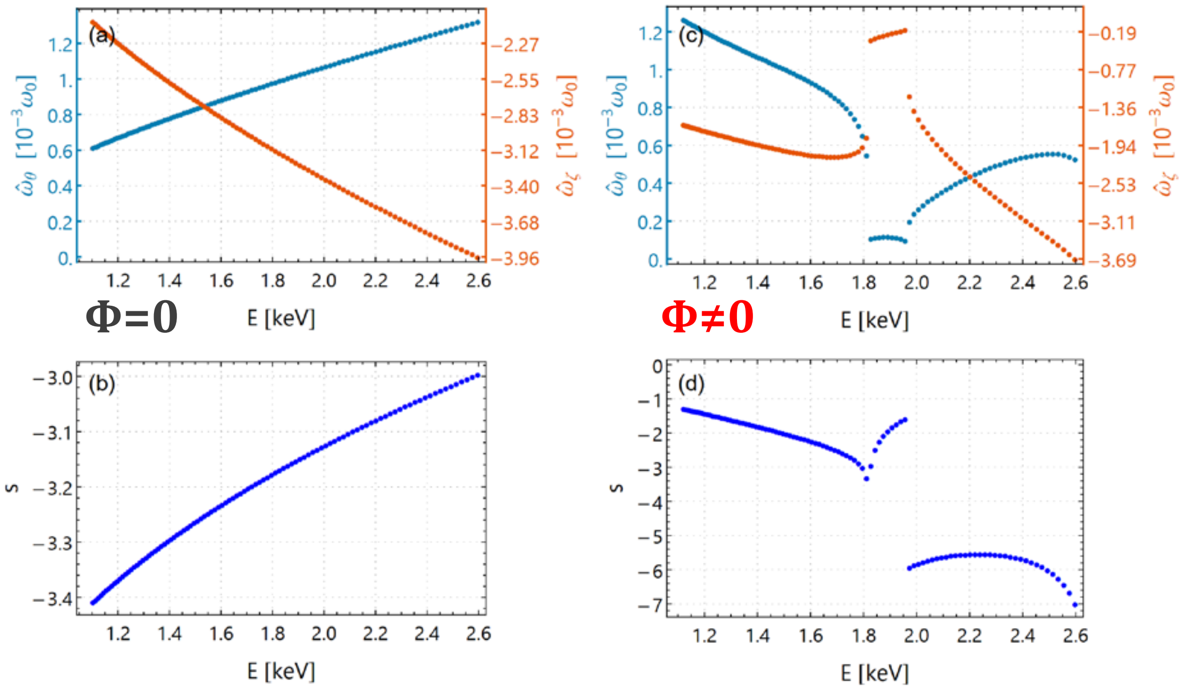


*The analytical knowledge of the full skeleton of the **resonance structure**, allows to pinpoint the exact locations of resonances in the phase space.*

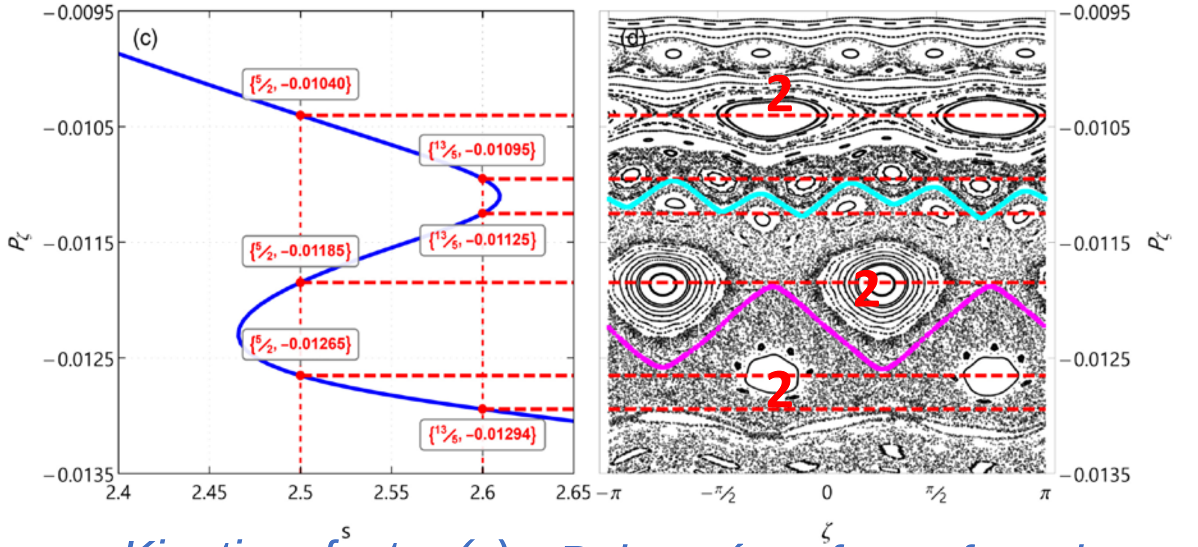
Fusion Plasmas – Radial electric field (H-mode)

The presence of the edge radial electric field (inherent to H-mode operation):

- Drastically **modifies the orbital frequencies** (bounce/transit, toroidal precession)
- Changes **the locations of resonant interactions** with perturbative modes
- **Enables or prevents** resonant interactions with specific modes
- Enables the formation of **Transport Barriers**
- Drastically **modifies particle, momentum and energy transport**



Orbital Spectrum (first row) and kinetic-q factor (s) (second row), without (left) and with (right) edge radial electric field.



Kinetic-q factor (s) *Poincaré surface of section*

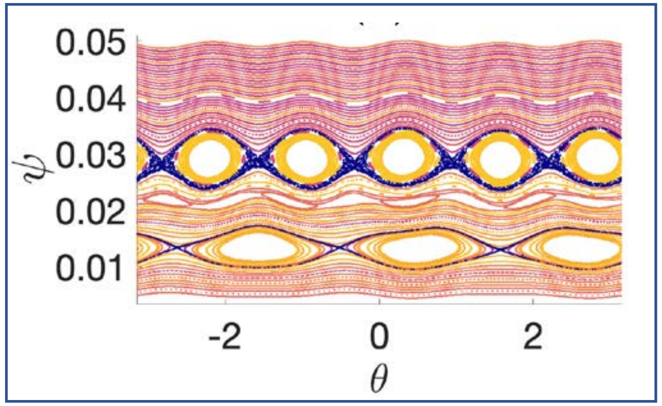
*The kinetic-q factor (s) predicts the **exact locations of the resonances**.*

*Local extrema correspond to locations of **Transport Barriers**.*

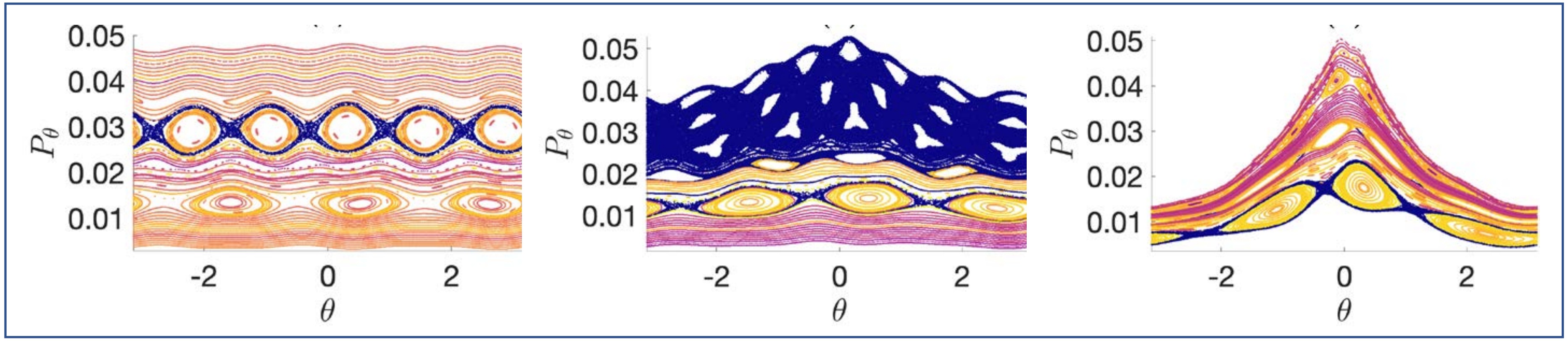
Fusion Plasmas – Magnetic/Kinetic Chaos Detection

Kinetic versus Magnetic Chaos in Toroidal Plasmas: A systematic quantitative comparison

- Chaoticity determines transport properties and confinement performance of a fusion device
- Kinetic chaos is related to magnetic chaos only for low-energy particles
- Energetic particles undergo large drifts across the magnetic field lines and have different chaoticity



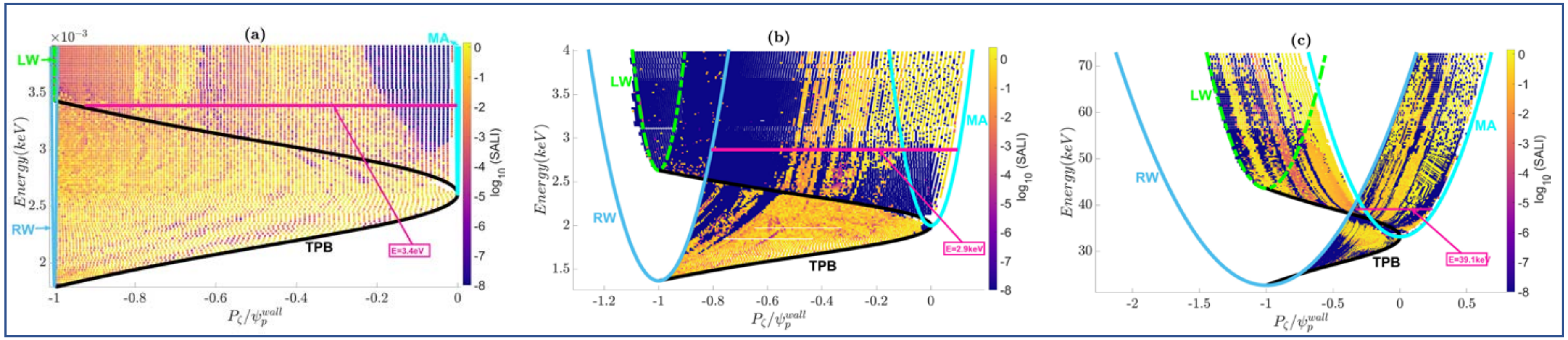
Magnetic field lines



*Particle orbits (**increasing energy →**)*

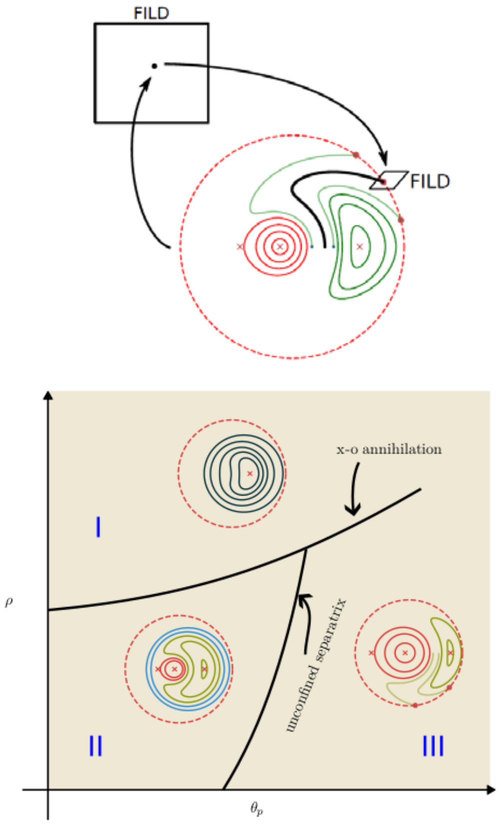
Overview of orbit chaoticity and its relation to confinement

Chaos quantification: Smaller Alignment Index (SALI)

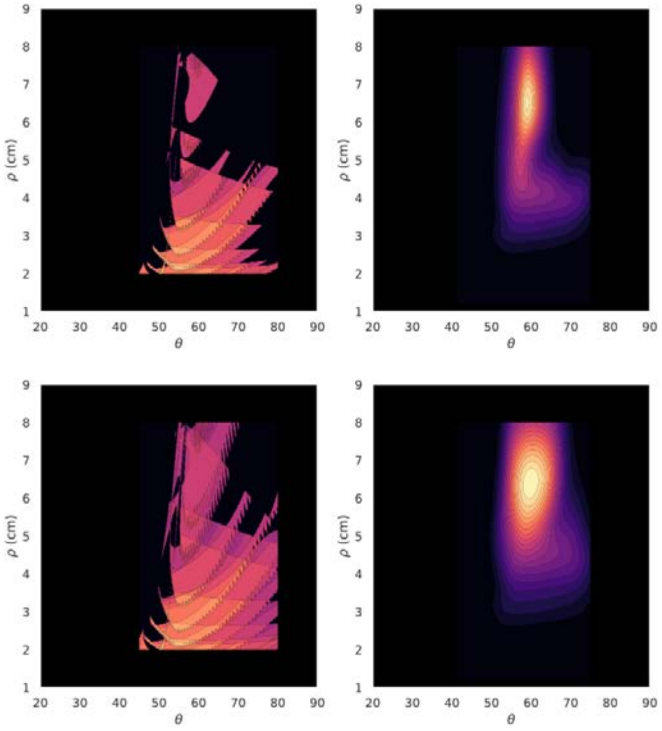


Fusion Plasmas – Fast Ion Losses

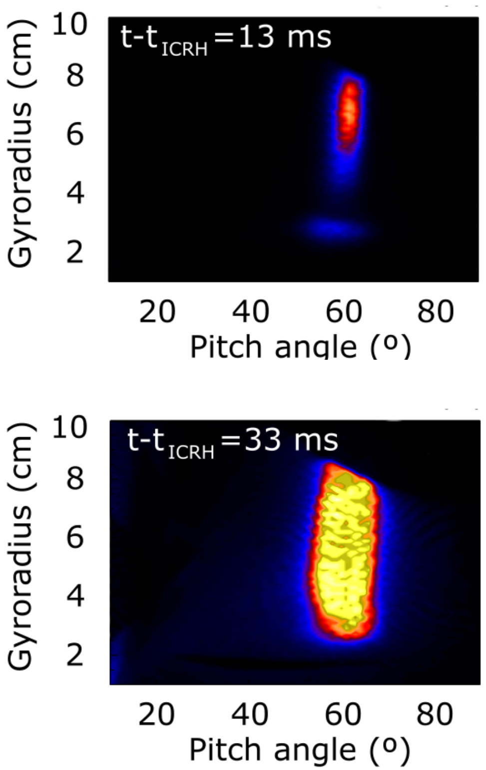
- **Estimate FI losses** by means of the distribution of unperturbed resonance orbits.
- **Resonance Index**: Measure of susceptibility to chaotic transport by means of resonance overlap
- **Comparison with experimental results:** Fast Ion Loss Detector (FILD)



Phase diagram of orbit topology on the FILD plane



Resonance index and synthetic FI loss signal for different snapshots

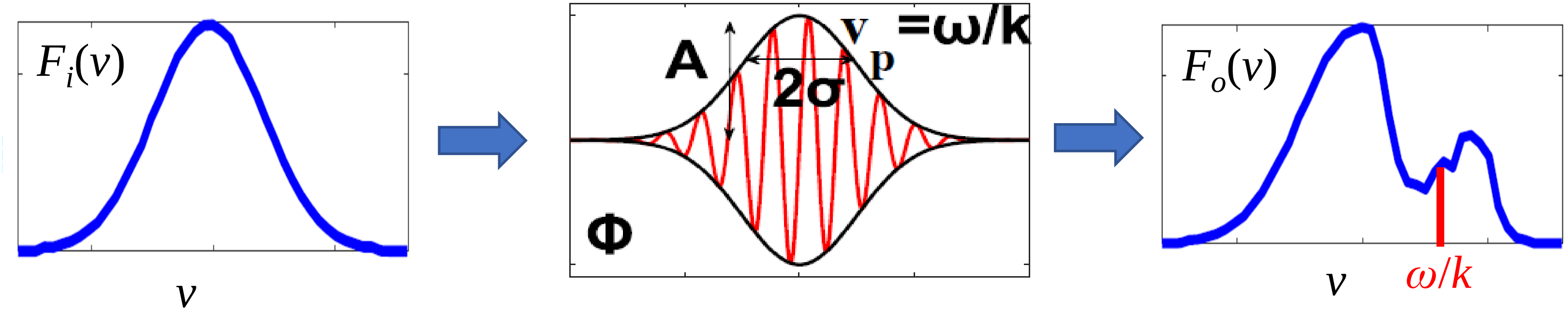


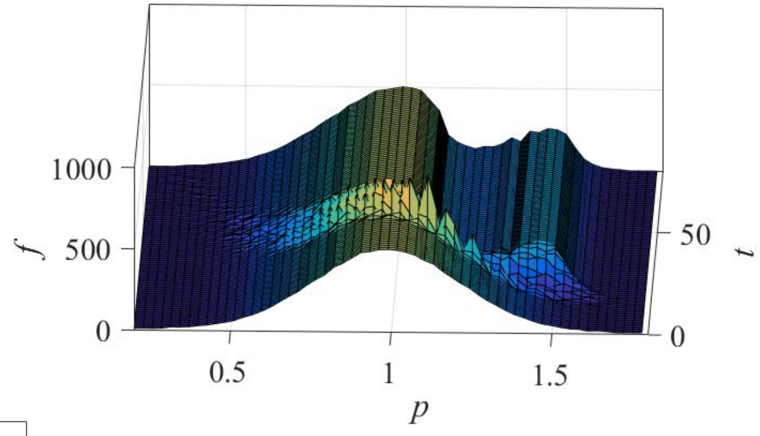
FI losses measured by FILD probe

Fusion Plasmas – Wave-particle interactions

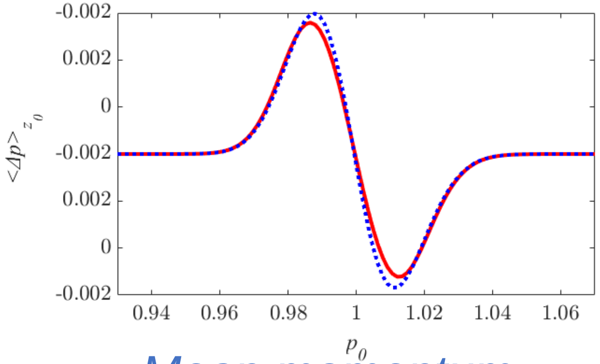
Study of Particle interactions with Spatially Localized Wavepackets

- Small-Amplitude Perturbations: Analytical results using Canonical Perturbation Theory
- Higher-Amplitude Perturbations: Systematic numerical investigation

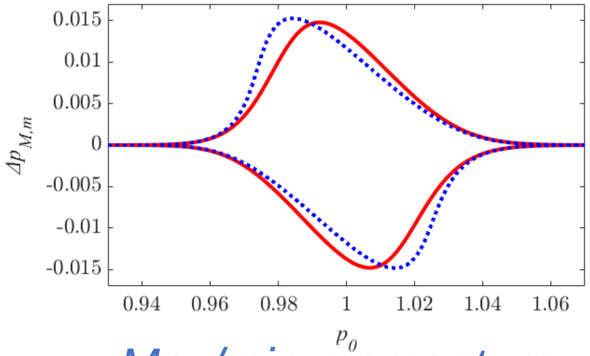




Time evolution of a Maxwellian momentum distribution function

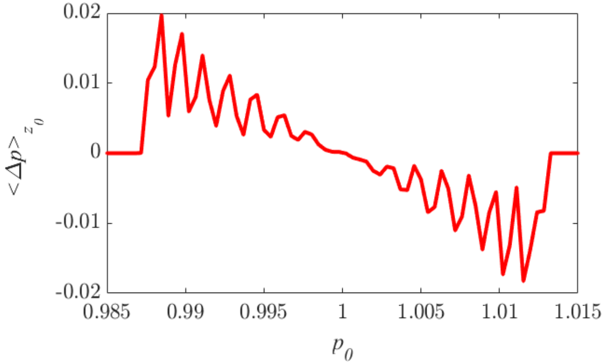


Mean momentum variation



Max/min momentum variation

Analytical (blue) and numerical (red) results for Small-Amplitude Perturbations



Mean momentum variation for Higher-Amplitude Perturbations

Nonlinear Photonics – Topics and Approach

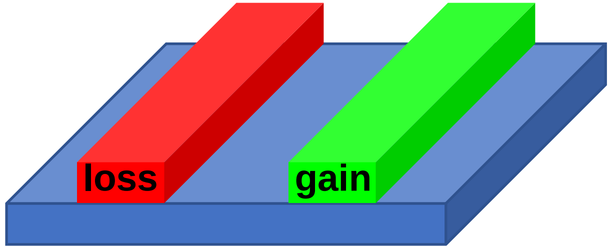
Topics:

- Self-localization and nonlinear wave propagation in complex media
- Non-Hermitian photonics
- Arrays of coupled semiconductor lasers
- Exploitation of the interplay between **inhomogeneity** (topology), **non-Hermiticity** (gain/loss) and **non-linearity** for complex dynamical behavior useful for **photonic circuits, sensors** and **tunable photonic oscillators**

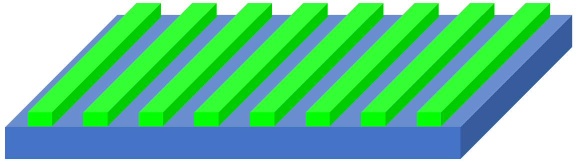
Approach:

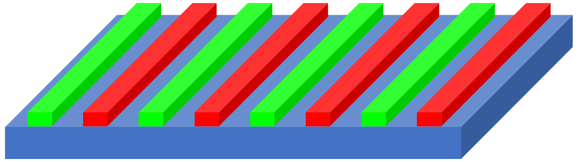
- Phase space analysis of self-localization dynamics
- Reduced models (effective particle) for complex wave propagation
- Coupled mode and rate equations models
- Bifurcation analysis in the parameter space
- Phase response and synchronization dynamics

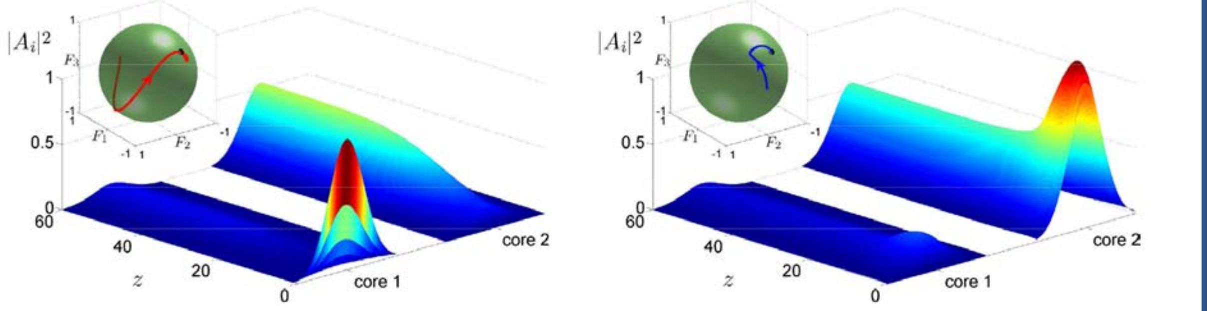
Nonlinear Photonics – Active Waveguide Arrays



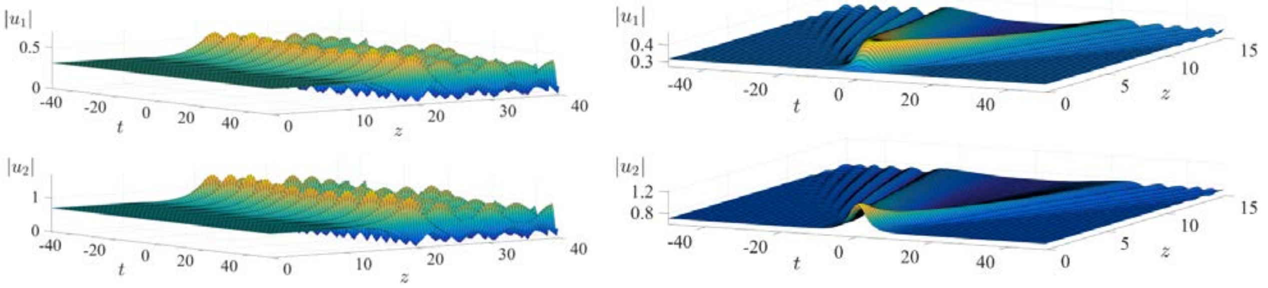
Discrete and **continuous, non-Hermitian** photonic structures.



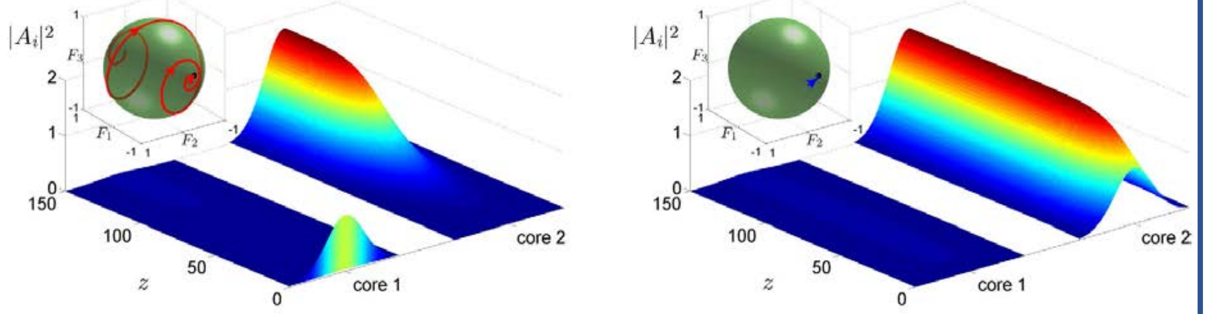




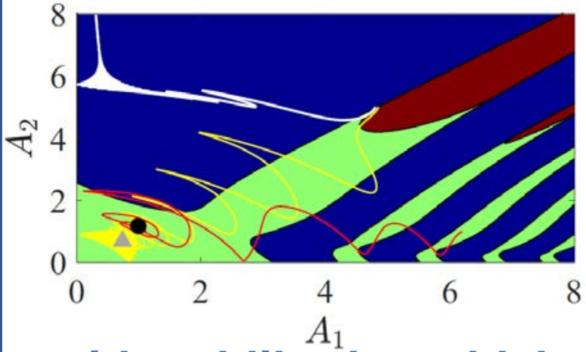
Stable Nonlinear Supermodes



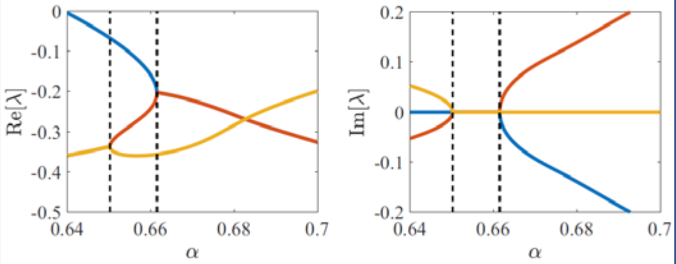
Modulational Instability/Stability



Optical Isolation “optical diode”

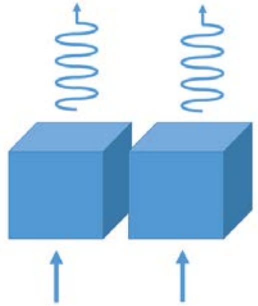


Multi-stability (sensitivity to initial conditions)

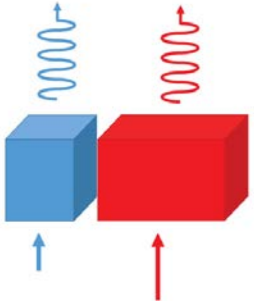


Exceptional Points (spectral degeneracies)

Nonlinear Photonics – Coupled Semiconductor Lasers



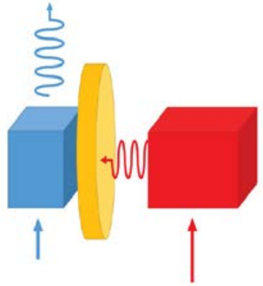
evanescently coupled identical lasers



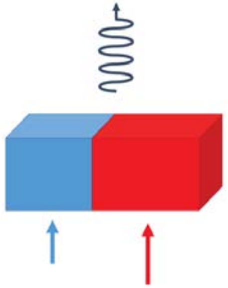
evanescently coupled differentially pumped dissimilar lasers

Tunable "photonic molecule" building block for more complex active photonic structures.

<u>Key parameters</u>:
frequency detuning $\Delta = \omega_2 - \omega_1$,
differential pumping $P_1 \neq P_2$



optically injected laser (OIL)



gain-lever configuration

Configurations of Coupled Semiconductor Lasers (CSL)

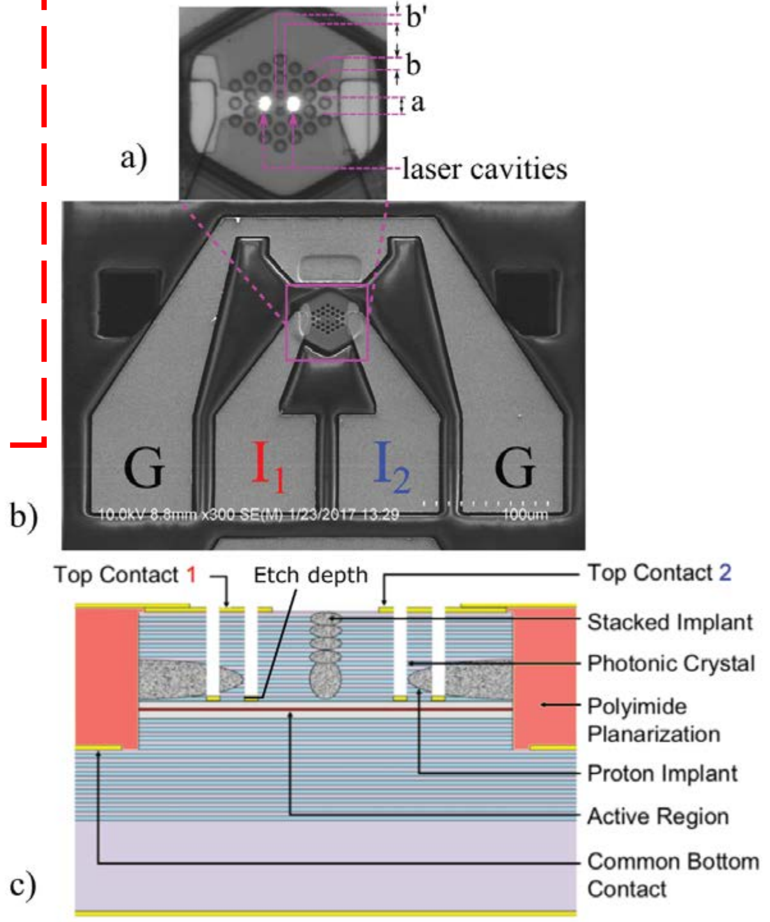


Fig. 1. (a) Top-view optical image of 2 × 1 ion-implanted photonic crystal VCSEL array with both cavities biased at threshold. (b) Scanning electron microscope image. (c) Side view sketch.

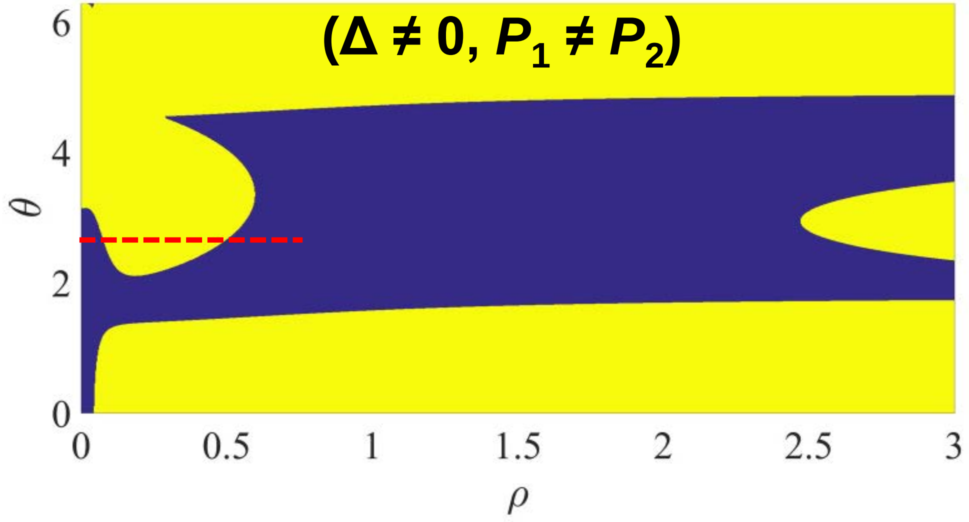
K.D. Choquette, IEEE JSTQE 25, 1700208 (2019)

Nonlinear Photonics – CSL: Stable Phase-Locking

Controllable asymmetry of the phase locked states

Applications:

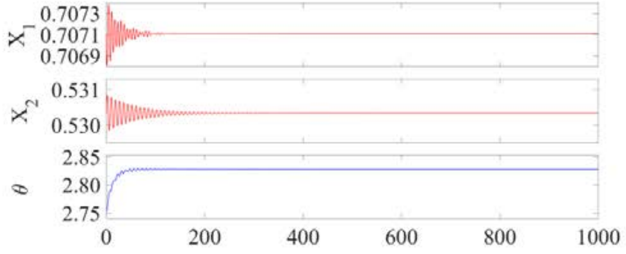
- **high-speed, non-mechanical beam steering**
- **on-demand waveform generation**



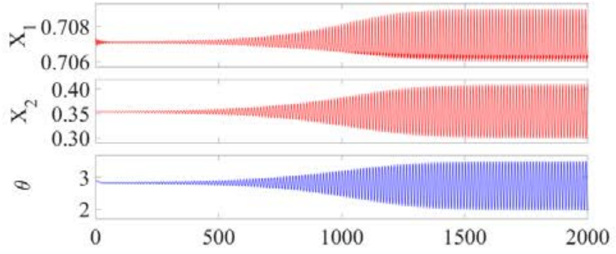
Stability diagram of Phase-Locked states

$\rho = E_2/E_1$ (electric field amplitude ratio)

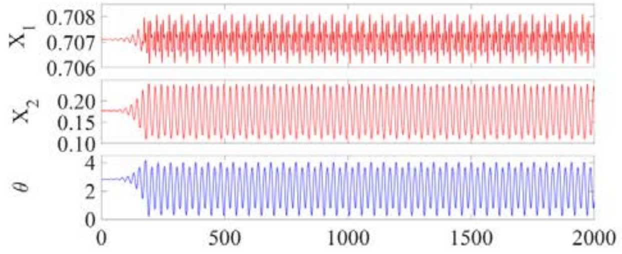
θ (phase difference)



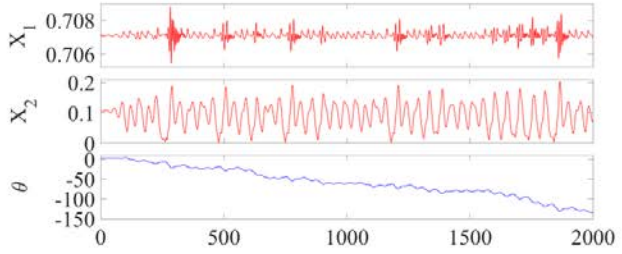
stable phase-locked state



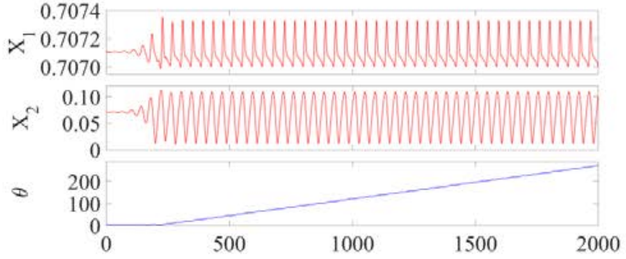
stable limit cycle



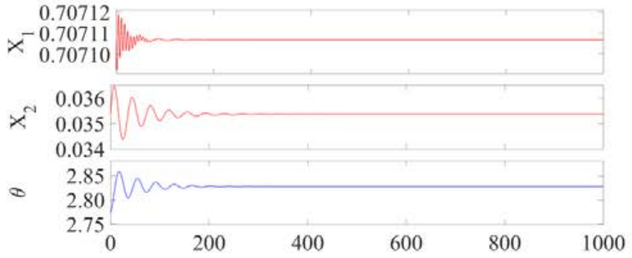
stable limit cycle



chaotic state



stable limit cycle



stable phase-locked state

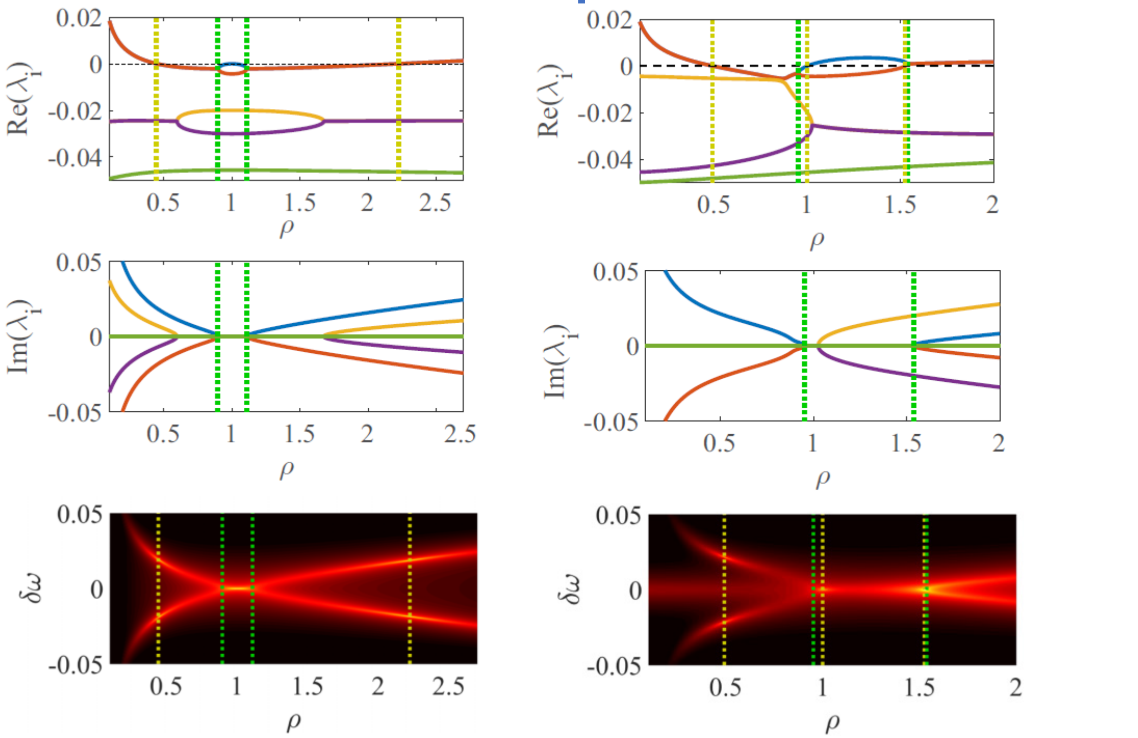
Nonlinear Photonics – CSL: Stable Phase-Locking

Spectral Signatures of Exceptional Points and Hopf Bifurcations

Applications:

- **tailored noise response (sensors)**
- **tailored current modulation response (transmitters)**

noise response

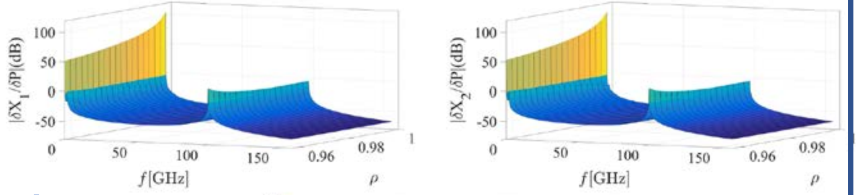


Exceptional (green) and Hopf bifurcation (yellow) points are manifested in the spectral line shape through the emergence of side bands and intensity peaks.

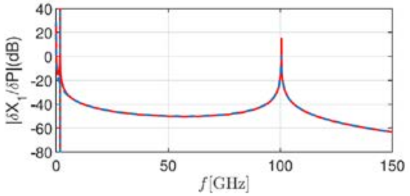
current modulation response

STRONG COUPLING

out-of-phase modulation

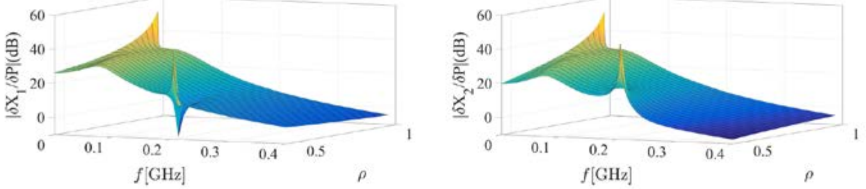


The amplitude response is peaked at much higher frequency (beyond 100 GHz) than the free running relaxation frequency

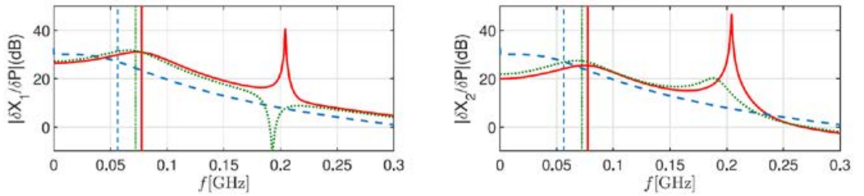


WEAK COUPLING

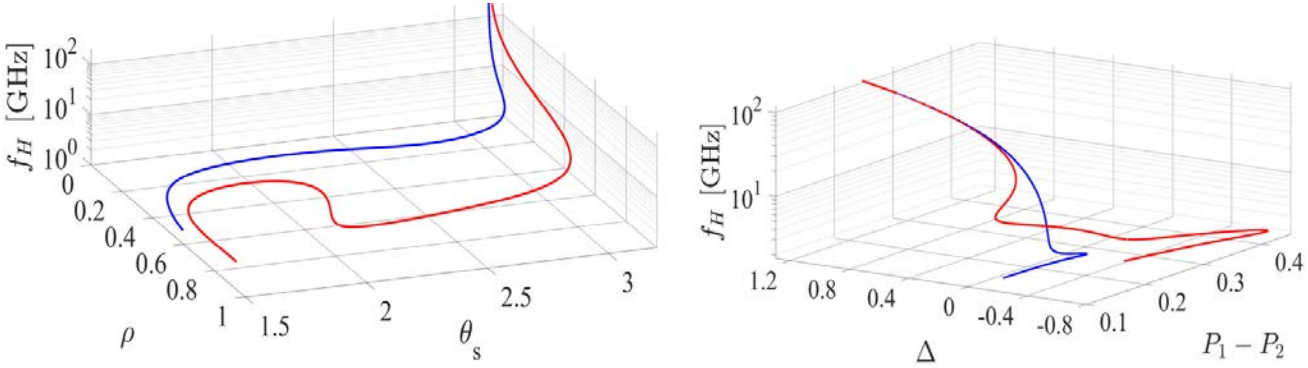
in-phase modulation



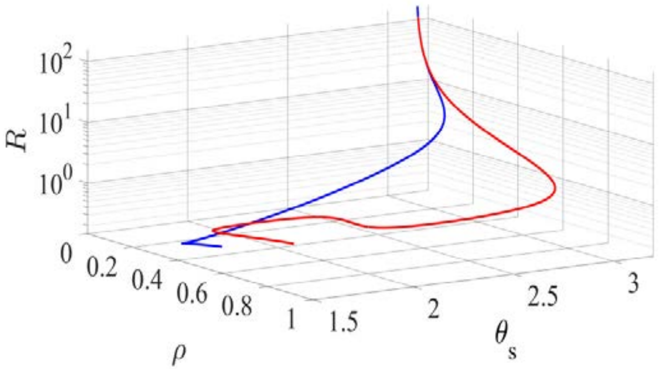
Sharp resonances and antiresonances appear for strongly asymmetric phase-locked states, close to Hopf points



Nonlinear Photonics – CSL: Tunable RF Oscillations



Hopf frequencies f_H of stable limit cycles as functions of the asymmetry (ρ) and the phase difference (θ_s) of the corresponding phase-locked state as well as of the pumping difference P_1-P_2 and detuning Δ.



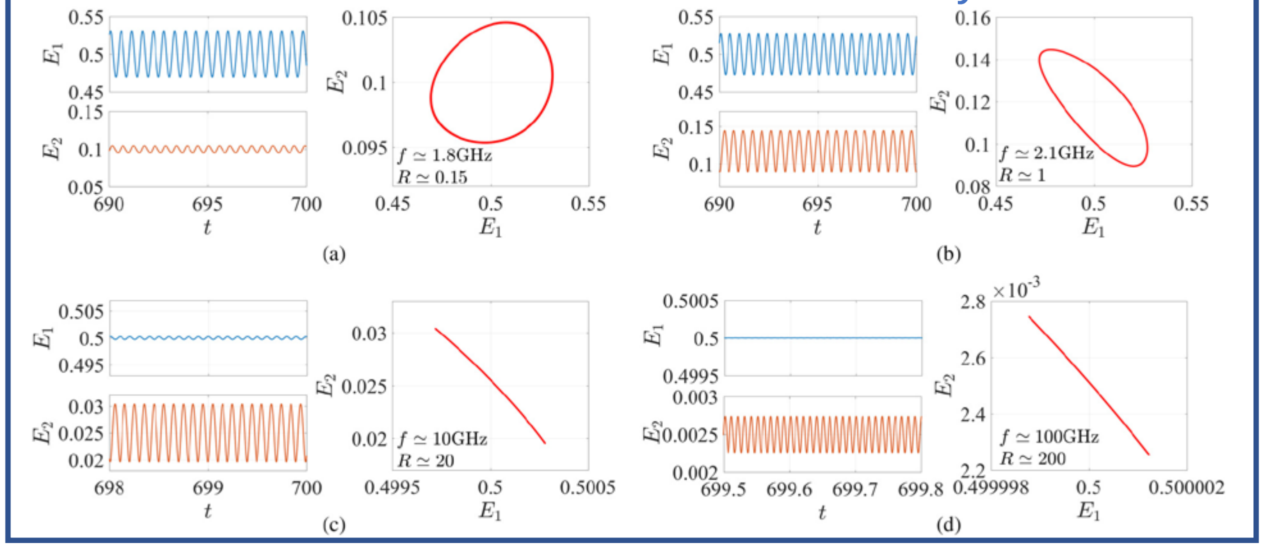
Oscillation amplitude ratios (R) as a function of ρ and θ_s.

Radically tunable stable RF oscillations

Applications:

- **Frequencies ranging from a few to more than a hundred GHz (widely varying degree of asymmetry between the lasers)**
- **Directly controllable via differential pumping and/or frequency detuning**
- **Multi-functional oscillator for chip-scale radio-frequency photonics applications**

Characteristic cases of stable limit cycles

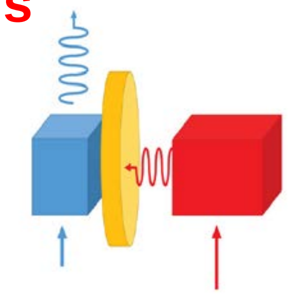


Nonlinear Photonics – OIL:Isochrons/Synchronization

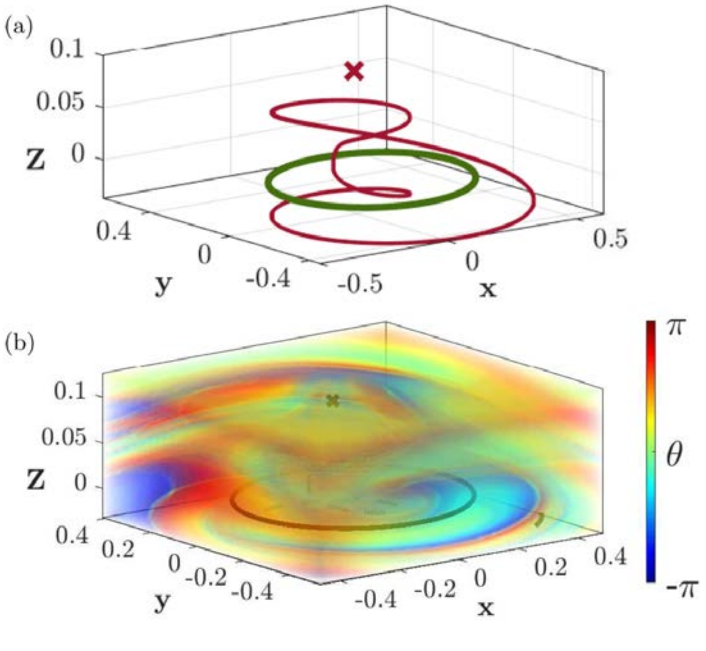
Isochrons, Phase Response and Synchronization dynamics of Optically Injected Lasers

Applications:

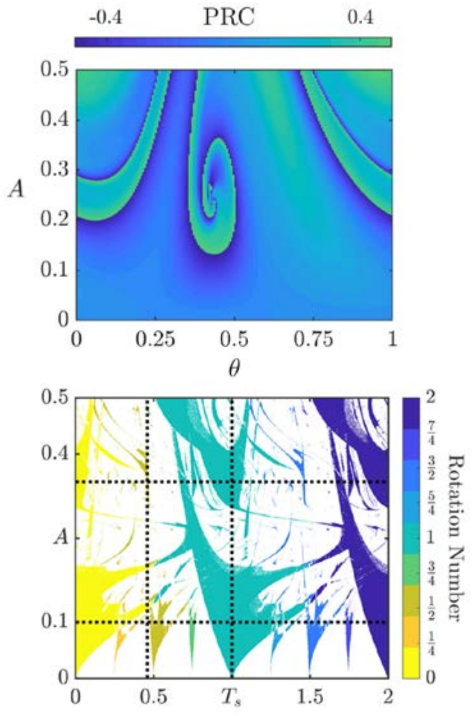
- **ultra-fast modulation (transmitters)**
- **controllable chaos (secure communications)**
- **frequency comb shaping (frequency synthesis, ranging, waveform generation)**
- **precise time measurements – photonic clocks (time-of-arrival, geo-location)**



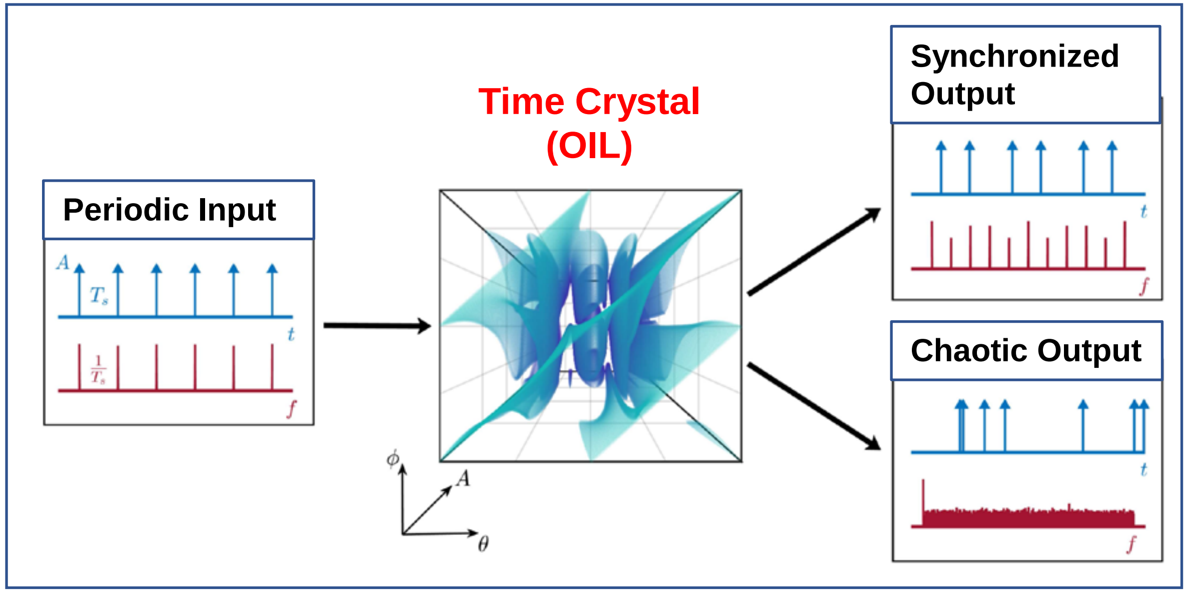
Optically Injected Laser (OIL)



Stable limit cycle (black) and its **Isochrons** structure



Phase Response (top) and **Resonance diagram** (bottom)

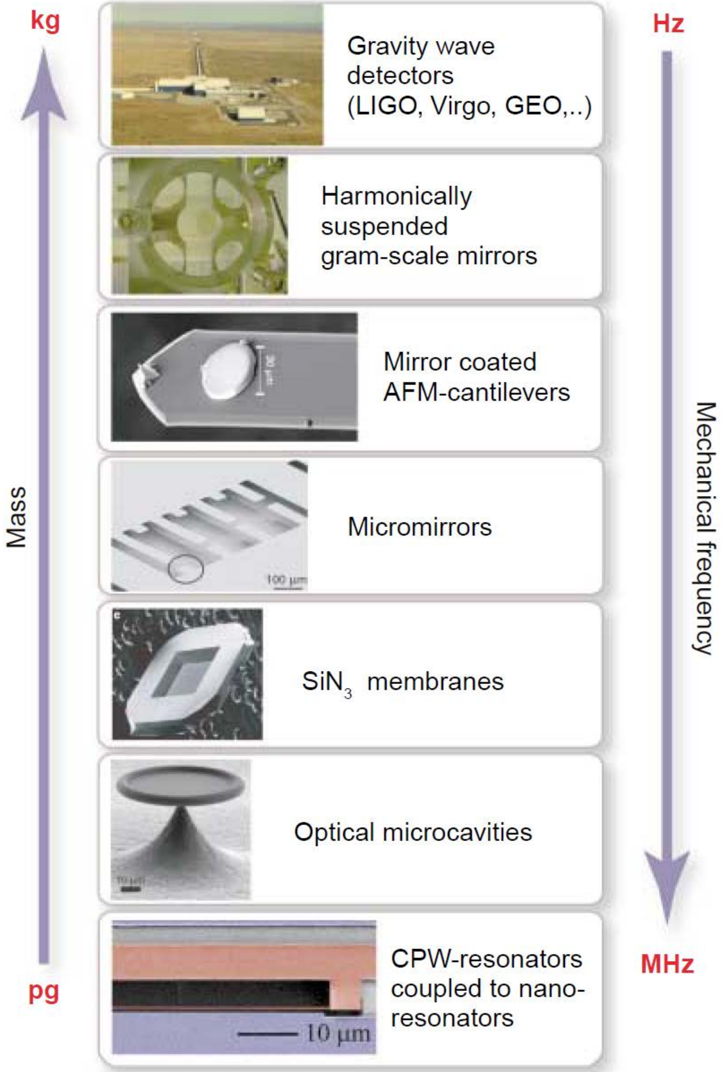


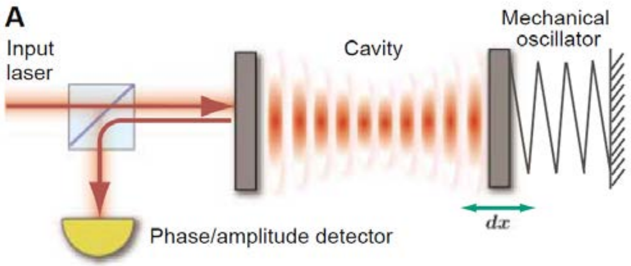
Frequency Comb shaping

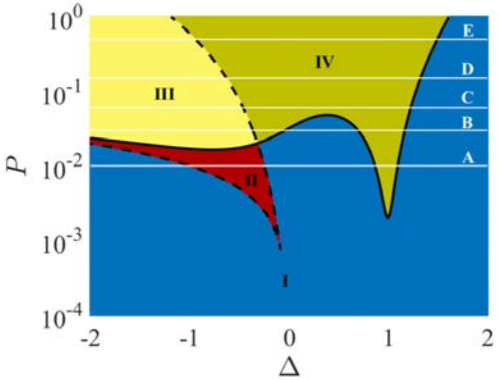
Nonlinear Photonics – Optomechanical Oscillators

Optomechanical Oscillators

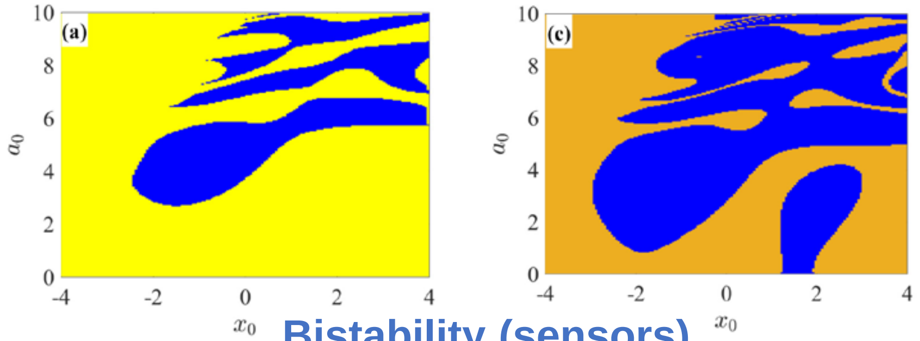
Applications:



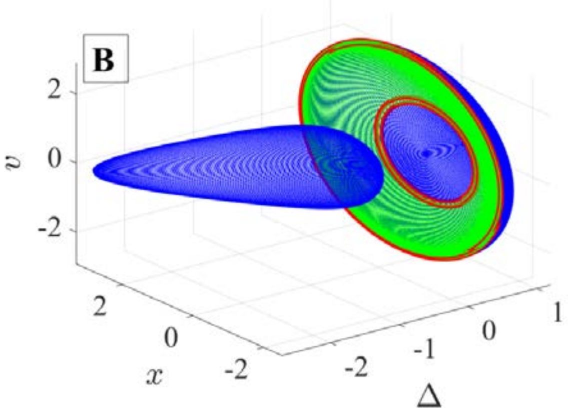




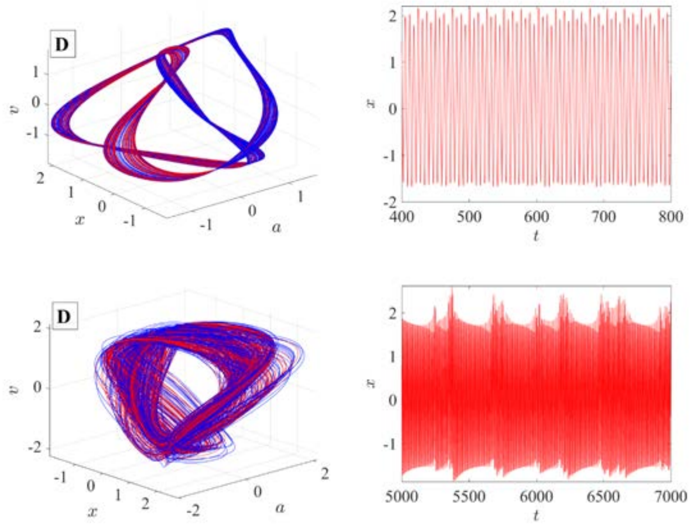
Steady states



Bistability (sensors)



Limit cycles (self-sustained oscillations)



Self-modulated and chaotic oscillations